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Operation of a 100,000 Volt Transformer

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OPERATION OF A 100,000 VOLT TRANSFORMER

BY

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

JOHN WILLIAM ANDREE and TRYGVE JENSEN

ENTITLED OPERATION OF A 100,000-VOLT TRANSFORMER

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE

OF BACHELOR OF SCIENCE IN ELECTRICAL ENGINEERING

Morgan Brooks.

HEAD OF DEPARTMENT OF ELECTRICAL ENGINEERING

CONTENTS

OPERATION OF A 100000 VOLT TRANSFORMER

I. OBJECT:-

It has been noticed by engineers operating high tension transmission stations, that sometimes on closing the transformer switches excess voltages occur on the high tension side. These excessive voltages occur only on closing the primary circuit and manifest themselves by sparking between the high tension lines.

It is the object of this thesis to investigate these excess voltages and their causes, and to devise some remedy for preventing the same.

II. TRANSFORMER EMPLOYED IN TESTS:-

The transformer employed in all the experiments is a 100000 volt transformer, built as a thesis for the degree of B.S., 1906, by Messrs. Hellman and Dixon. It has a capacity of 10 K.W. wound for 440 volts, 60 cycles p primary. Both primary and secondary coils are divided, the transformer being of the core type. The transformer is immersed in kerosene, and for safety, as well as to diminish the strain on the high tension windings, the middle point of the latter is connected to the core which is permanently grounded.

For further particulars concerning the transformer, see the thesis referred to.

III. SPARK CAP:-

As the voltages to be measured exist only momentarily, it was necessary to employ a voltmeter that, besides measuring voltages of 100000 volts and above, would give indications of momentary voltages. It might have been possible to employ a test coil and ballistic galvanometer, but this method has the disadvantage that, in case of leakage, the result would be erroneous; besides this method would take considerable time, and in a case like this, where hundreds of readings had to be taken, it would not be practical.

It was, therefore, decided at the outset to employ a spark gap. No such instrument existed in the laboratory, and consequently had to be constructed. The specifications issued by the American Institute of Electrical Engineers were not then published, and we had to use our own judgment.

Fig. 1 shows the dimensions of the spark gap, and Fig. 2 shows a photograph of the same. Marble was used for foundation and brass for the rods. A grooved pulley was placed on post A to allow the gap to be operated by means of a silk cord from a distance. The calibration for this spark gap was obtained from the Standardization Report, 1907, of the American Institute

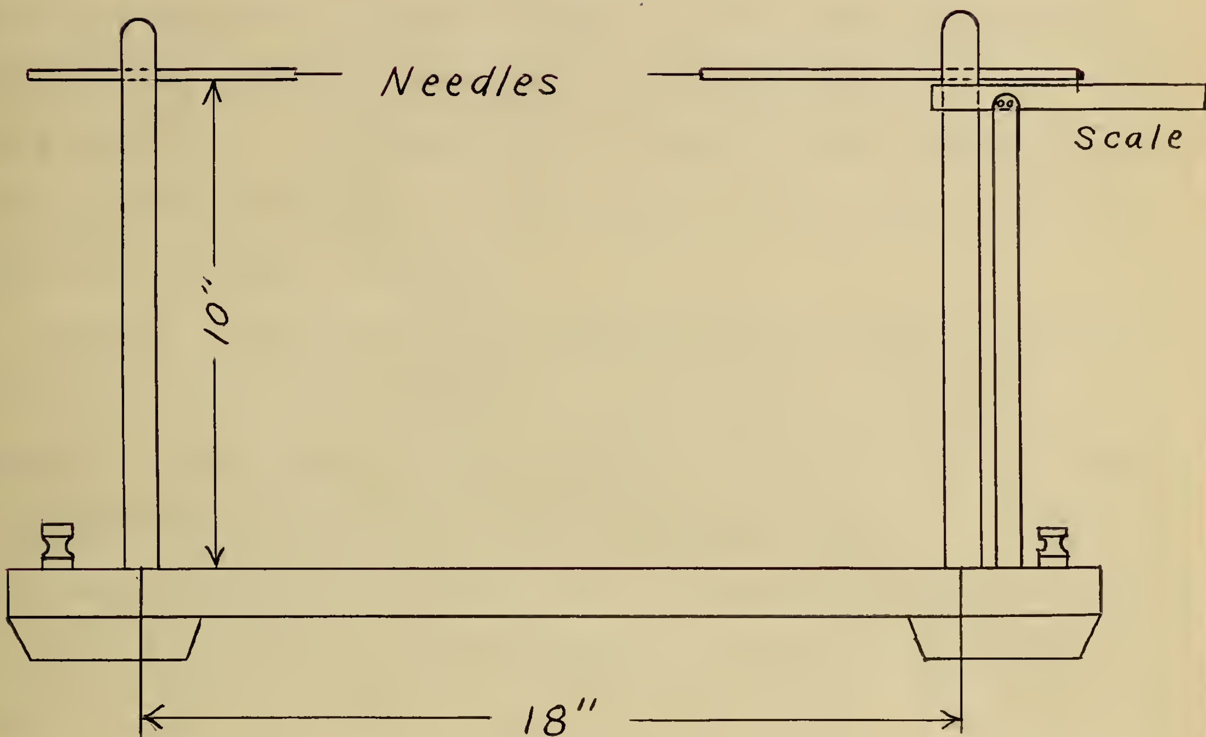


Fig. 1.

Fig. 2.

of Electrical Engineers, and were transferred directly to the scale of the spark gap, so that the voltage could be read directly. It is not known definitely whether the spark gap gives the maximum voltage or the effective voltage, or what, but it seems to us that it is most likely to indicate the maximum voltage, inasmuch as it depends for its indication upon the breakdown of air insulation. It will be assumed, therefore, in this treatise that all spark gap readings are maximum voltages, while it is of little significance whether it is maximum or effective.

According to the spark gap specifications issued recently by the American Institute there should be placed in series with the spark gap a resistance - in ohms - equal to half the maximum voltage for which the instrument is built. As in the present case the spark gap was built for 100000 volts, 50000 ohms had to be inserted. The resistance was obtained by means of graphite enclosed in a glass tube about 10 feet long, and 1/4 inch in diameter.

IV. ARRANGEMENT OF APPARATUS:-

The transformer is located in a special room in the basement of the Electrical Engineering laboratory. To prevent any accident all possible safety devices were employed. Fig. 3 is a plan of the laboratory; Fig. 4, the diagram of the connections, and Fig. 5 a photograph showing the general arrangement.

An iron fence encloses all high tension circuits and apparatus. Attached to the gate is the handle of a switch arranged in such a way that, whenever the gate is opened the switch opens automatically, opening the primary circuit of the transformer. A grounded wire netting was suspended over the high tension circuits to prevent static disturbances in the wires attached to the ceiling.

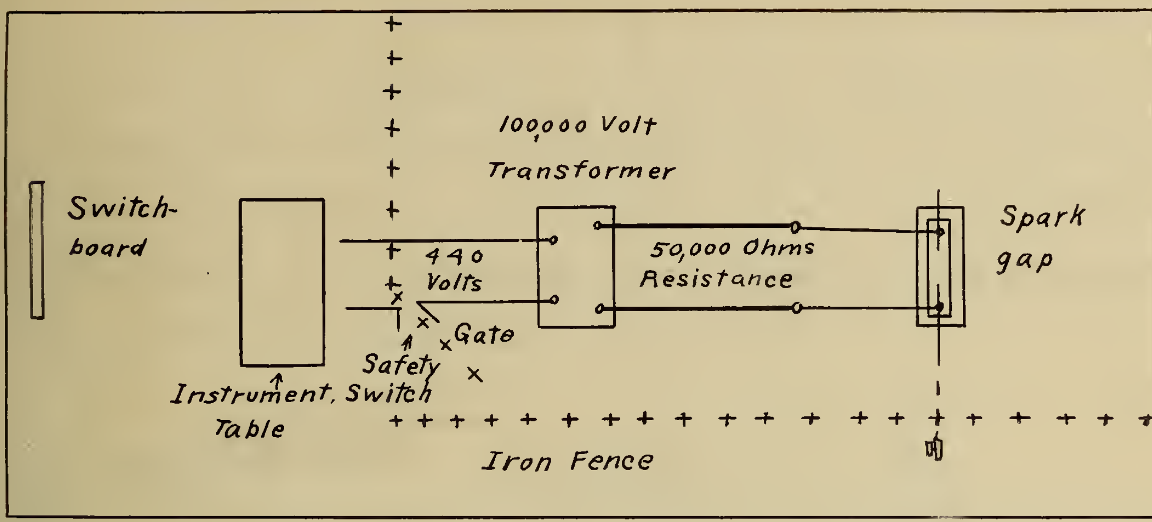


Fig. 3

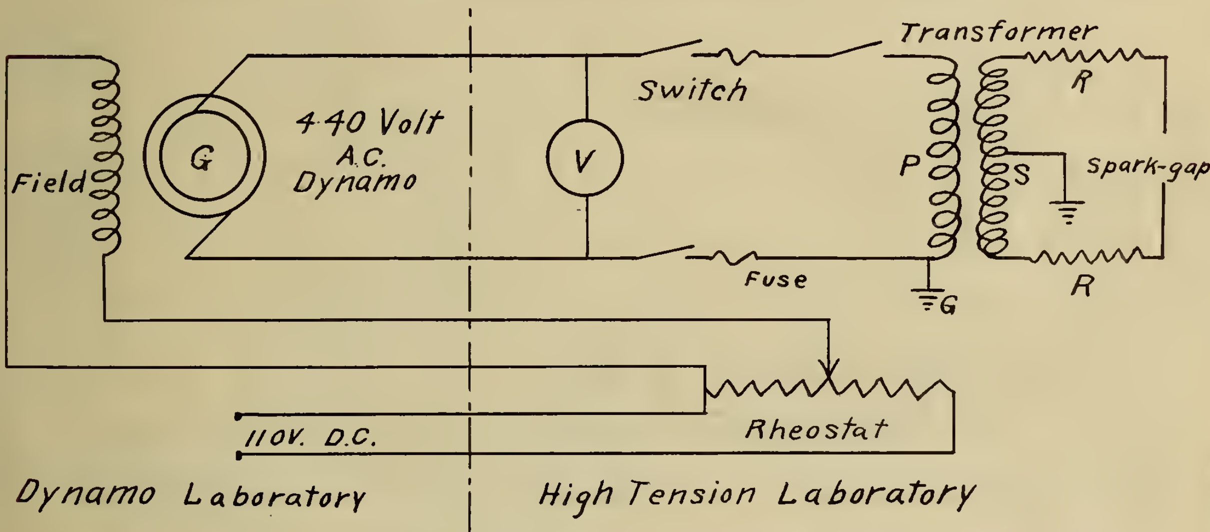


Fig. 4.

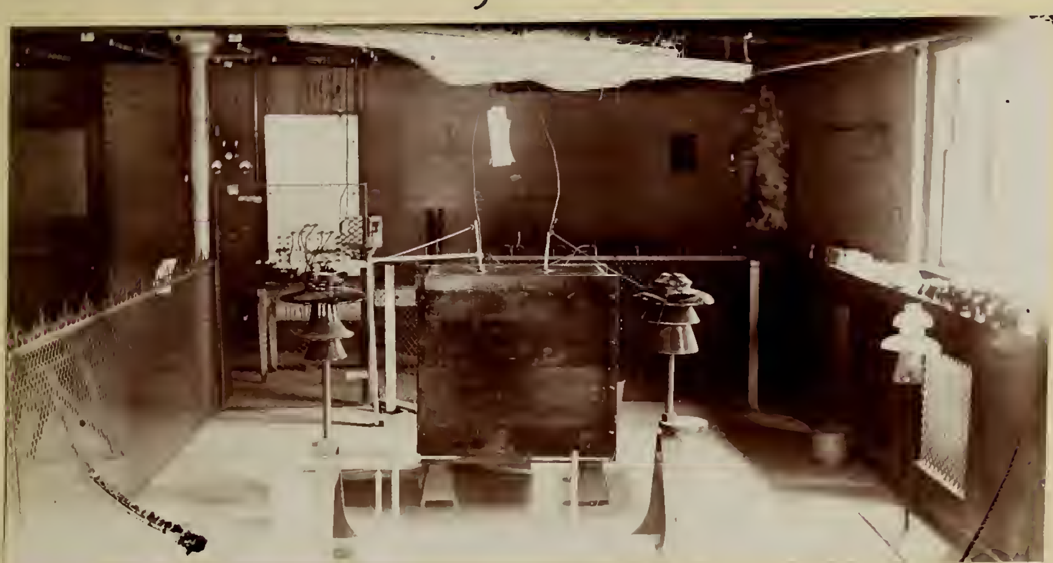


Fig. 5.

The current was obtained from a 440 volt 60 cycle Westinghouse Rotary converter of 10 K.W. capacity, belt driven by a Westinghouse 15 Hp motor. These machines are located in the main laboratory, and the generator was connected to the high tension laboratory through the main switchboards. The voltage was controlled by means of a stove pipe rheostat adjacent to the switchboard in the basement.

V. PRELIMINARY TESTS:-

With these arrangements and apparatus the preliminary tests were started to ascertain to what extent the excess voltages referred to manifest themselves.

Needles - #5 - were used in the spark gap as electrodes, and these were renewed whenever a discharge or spark went across the gap, to maintain constant conditions. The primary voltage was raised until the spark gap indicated the voltage desired. The primary voltage was then maintained constant and the switch closed and opened a number of times to determine the highest secondary voltage obtainable on closing the circuit. It was found that the momentary secondary voltage rises as high as 40% above the normal one time out of 25 times that the circuit is closed.

VI. THEORY:-

The secondary voltage of a transformer is equal to the time rate of change of flux. Hence these excess voltages must be due to a high rate of change of flux on closing the primary circuit. It was, therefore, natural to assume that this high rate of change of flux might be due to residual

Note: In what follows, primary is used to signify the low tension, and secondary the high tension side of the transformer.

magnetism in the iron of the transformer. If magnetised in one direction and the switch is closed so as to produce a flux in the other direction there would be a high rate of change of flux. Suppose, in Fig. 6, the iron is magnetised to the point "a", and that the circuit is closed on the point of

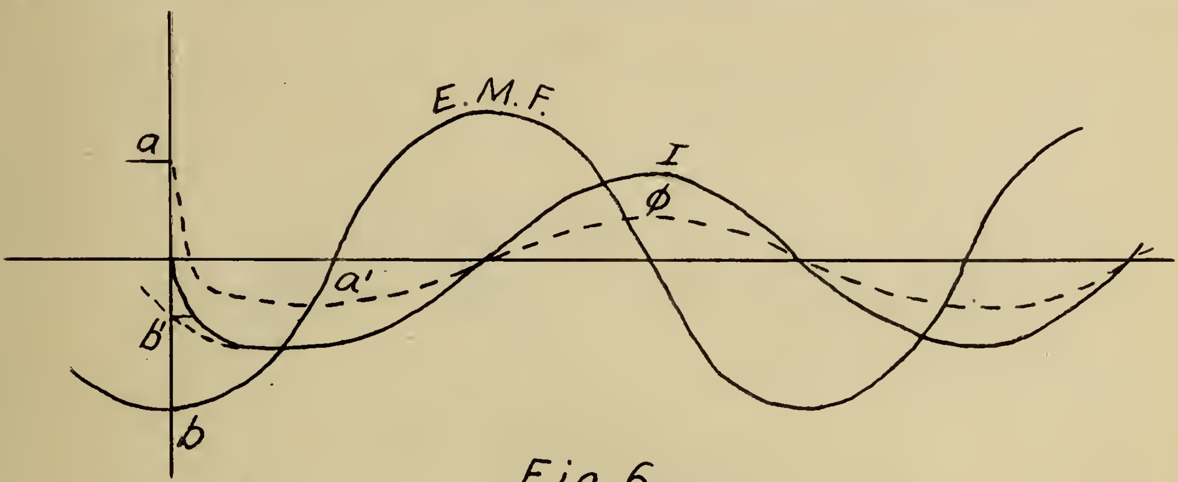


Fig. 6.

the E. M. F. wave "b"; since on open secondary the flux is practically in phase with the primary current, the flux will have to change so as to be in phase with the current. Let the change take place along the curve a-a'; it is seen that the change is much more rapid than during normal action, and this would result in excess secondary voltage.

Let us next ignore the residual magnetism. Is it not possible that a high rate of change of flux can be produced even if the iron is demagnetised? It has been stated by Professor Morgan Brooks that the reactance of a transformer, so far as it depends upon the magnetizing of the iron core, is absent on first closing the primary circuit; the initial current-rush being limited by the impedance of the winding considered as a solenoid without a core. As the core rapidly attains normal synchronous activity, the impedance rapidly increases to full value, reducing the current to normal. Although the entire action may be completed in a fraction of a second, there is nevertheless time for disastrous surges. Hence, if the normal voltage be impressed upon this

primary low-resistance winding, an excessive current will tend to flow. As the iron becomes rapidly magnetized, a high induced voltage will be produced in the primary that will immediately check this current, causing a rapid rate of change of flux, since on open secondary the flux practically is in phase with the current. See Fig. 7.

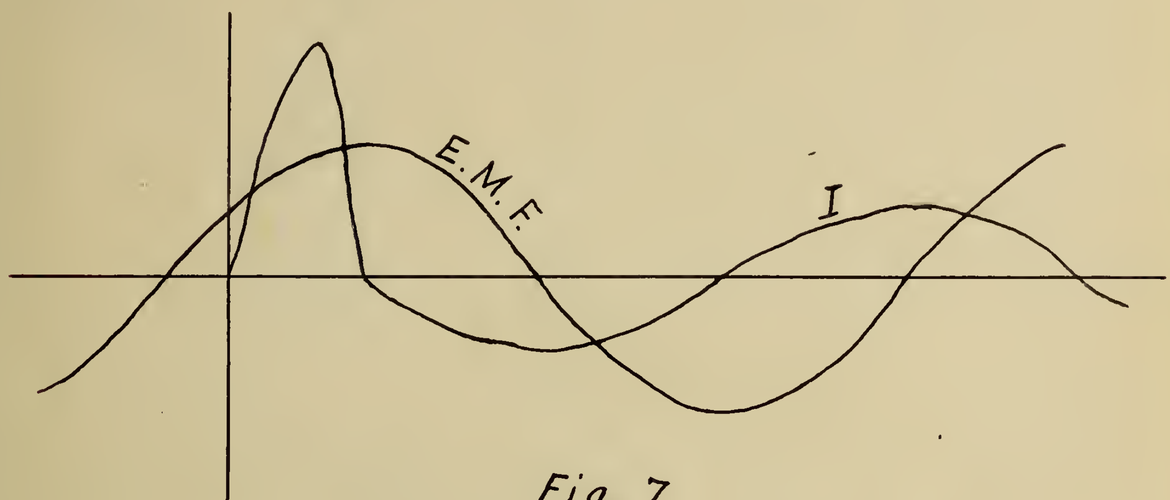


Fig. 7.

VII. SPECIAL SLIP-RING DEVICE:-

It is evident that in order to obtain any reliable results it is necessary to know at what point of the E. M. F. wave the circuit is closed, because the excess voltage varies considerably with the point of closing. Consequently a device had to be constructed by means of which the primary could be closed at definite points of the E. M. F. wave and remain closed, as under operating conditions. A contact method would not do, because as soon as the circuit was closed, it would again be opened, allowing no time for the current to flow. The operation was brought about by means of a special slip-ring attached to the generator shaft. This slip-ring when developed,

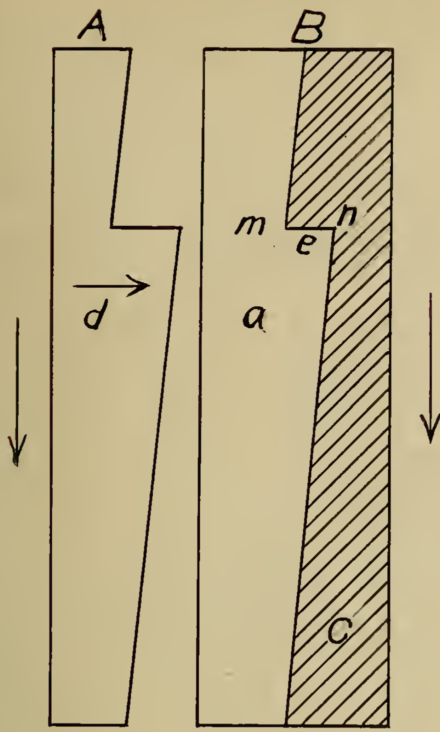


Fig. 8.

appears as in Fig. 8. A is the slip-ring, consisting of a part C of brass, and a part D of fibre. B is a cam-shaped cylinder revolving on the same shaft as A and keyed to it, but free to move axially on the shaft. Suppose now that the brush is at "a" and that the rings are in the position shown. If B is pushed in the direction of the arrow, d, while the shaft is rotating, B will get in contact with the brush and push it along, and if moved rapidly enough, the brush will make contact with the brass at E; if not, the cam will lose contact with the brush, but will regain it after part of a revolution, and will finally cause the brush to make contact at E. The cam should be moved fast enough so that the brush is pushed from "m" to "n" in one revolution of the shaft. A photograph of the attachment is shown in Fig. 9. Current is fed to the slip-ring by means of a fixed brush, as seen from the photograph.

For "Reliability of Results" by means of this attachment, see later.

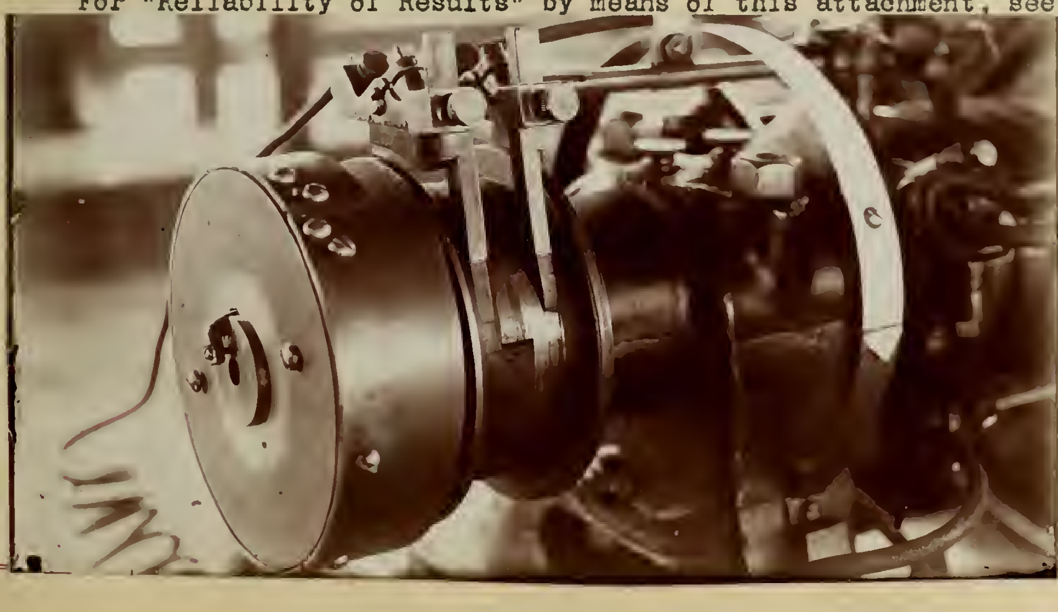


Fig. 9

VIII. GENERATOR E. M. F. WAVE AND GRADUATION:-

The generator E. M. F. was determined by the contact method. Connections were made as shown in Fig. 10. A contact piece was fastened to the slip-ring, and a brass spring substituted for the brush, adjusted so as to barely touch

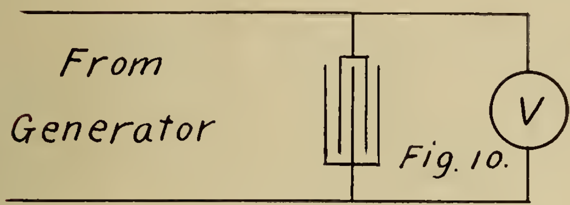


Fig. 10.

the contact piece. The brushholder was so arranged that it would be revolved, producing contact at any point of the E. M. F. wave.

The zero points were first determined; then the graduated scale was fastened in place, and readings were taken for every 9 degrees. The curve resulting is shown in Plate 2, plotted from the data given by Table 1.

IX. VARIATION OF SECONDARY VOLTAGE ON CLOSING THE CIRCUIT AT DIFFERENT POINTS OF THE E. M. F. WAVE:-

We were now prepared to begin the actual tests. The first step was to investigate the secondary voltages on closing the primary at different points of the E. M. F. wave. Connections were made as shown in Fig. 4, employing the special slip-ring attachment. Assuming at this point of our investigations that the secondary voltages are affected by the residual magnetism of the transformer iron, a series of readings were taken for secondary voltages on closing the primary circuit every 18 degrees along the E. M. F. wave from zero to 360 degrees, demagnetising the transformer iron previous to every reading.

After having demagnetized the transformer, by gradually reducing the E. M. F. to zero by means of the stove-pipe rheostat, shown by Fig. 4, the primary switches were closed with the slip-ring set so as to close the circuit on the desired point of the E. M. F. wave, and with the brush on the fibre. The circuit was then closed by pushing the brush on to the brass ring.

This was repeated for the same point of the E. M. F. wave until a spark gap distance was found for which a spark barely passed across the gap giving the secondary voltage occurring on closing the circuit at that point. The generator voltage was maintained constant throughout the test at such a value as to give a normal spark gap reading of 50000 volts.

RESULTS:- The result of this test is shown by Table 2, and the corresponding curve on Plate 3. It is seen from this curve that the secondary voltage is highest on closing the primary circuit at the maximum points of the E. M. F. wave, positive and negative, and lowest on closing the primary circuit at the zero points. While the normal operating secondary voltage was 50000 volts, the voltage on closing the circuit rises as high as 71000 volts, and never falls below 54000 volts; that is, it is impossible to close the primary switch so as not to produce a secondary voltage in excess of the normal.

RELIABILITY OF RESULTS:- The variation of the secondary voltage, as read by means of the spark gap, on closing the primary circuit at the same point of the E. M. F. wave, amounts to about 3%; this variation may be due partly to non-uniformity of the points of the needles used in the spark gap, and partly to imperfections in the circuit-closing device.

X. EFFECT OF RESIDUAL MAGNETISM:-

Having determined the variation of the secondary excess voltage on closing the primary circuit the object of the next tests is to investigate the causes of these voltages. As mentioned above it has been generally believed, that these excess voltages are chiefly due to residual magnetism in the transformer iron. If this were the case, a variation of secondary voltage would result by closing the primary circuit at the same point of the E. M. F. wave, with the transformer iron magnetized first in one direction

and then in the opposite direction. The transformer used is well adapted for such a test on account of the unusually high residual magnetism of its iron. The hysteresis curve for the transformer is shown on Plate 1, showing a residual magnetism of about 65%. This curve was obtained by the increment method by means of a test coil and ballistic galvanometer.

Three sets of experiments were performed:

1. The transformer iron was magnetized, say positively, by means of 25 amperes direct current, which is the full load primary current; the D. C. circuit was then removed, and the A. C. switches closed with the slip-ring brush on the fibre. The circuit was then closed at the desired point in the manner described above. This was repeated until the secondary voltage was ascertained.

2. The transformer iron was then magnetized in the opposite (negative) direction by means of the same current, and the test repeated as before.

3. Finally the transformer iron was demagnetized and the secondary voltage on the closing the primary determined as before.

This procedure was repeated for every 18 degrees along the E. M. F. curve.

RESULT:- The result of these tests is shown by Table 3, and the corresponding curves on Plate 4 on which are plotted the results for the three distinct conditions. It is seen that the curves are very similar and that the numerical values are substantially the same regardless of previous magnetization. Remembering that the readings for the same points of the E. M. F. wave were taken under exactly the same conditions the conclusion must be drawn, that <u>the residual magnetism has no effect upon the secondary excess voltage</u>. It should also be remembered that the transformer iron in the present case has a residual magnetism of 65%, and should consequently show a very marked effect, if residual magnetism were the cause of the excess secondary voltages. By 65% residual magnetism, we mean a residual magnetism

which is 65% of the magnetism to which the transformer is carried under full voltage full load conditions. This 65% would be about equal to 100% of the magnetism of the transformer, when operated at one half voltage, as was necessary in these experiments, to guard against breakdowns when the circuit was closed at critical points of the E. M. F. wave.

XI. PRIMARY CURRENT ON CLOSING CIRCUIT:-

Being satisfied, that the secondary excess voltage is not due to residual magnetism, the next step was to investigate the primary current on closing the primary circuit. This was done by means of an electromagnet of great sensitiveness. It was a Western Electric Telephone-Switchboard Signal, with a drop, actuated by the electro-magnet, as shown in Fig. 11.

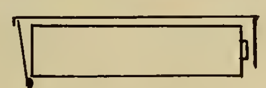


Fig. 11

This electromagnet was placed in shunt with a variable resistance, the latter being in series with the transformer primary. The connections are shown in Fig. 12.

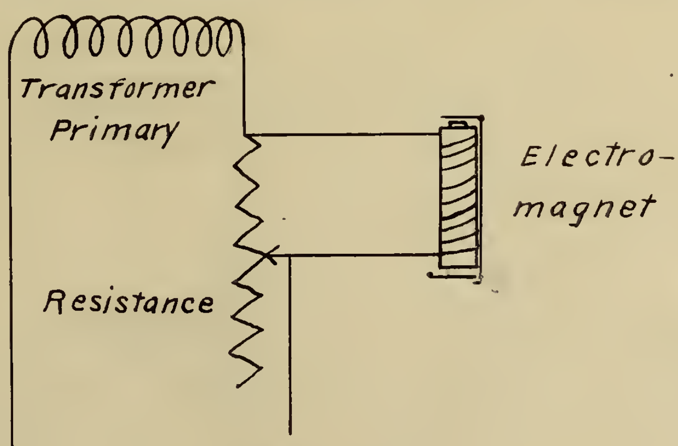


Fig. 12.

The experiment is based upon the assumption, verified by several trials both with direct and alternating current, that it always takes the same minimum current to actuate the drop of the electromagnet, whether the current

Diagram of Connections used for Determining the Rush of Primary Current on Closing the Primary Circuit of the Transformer.

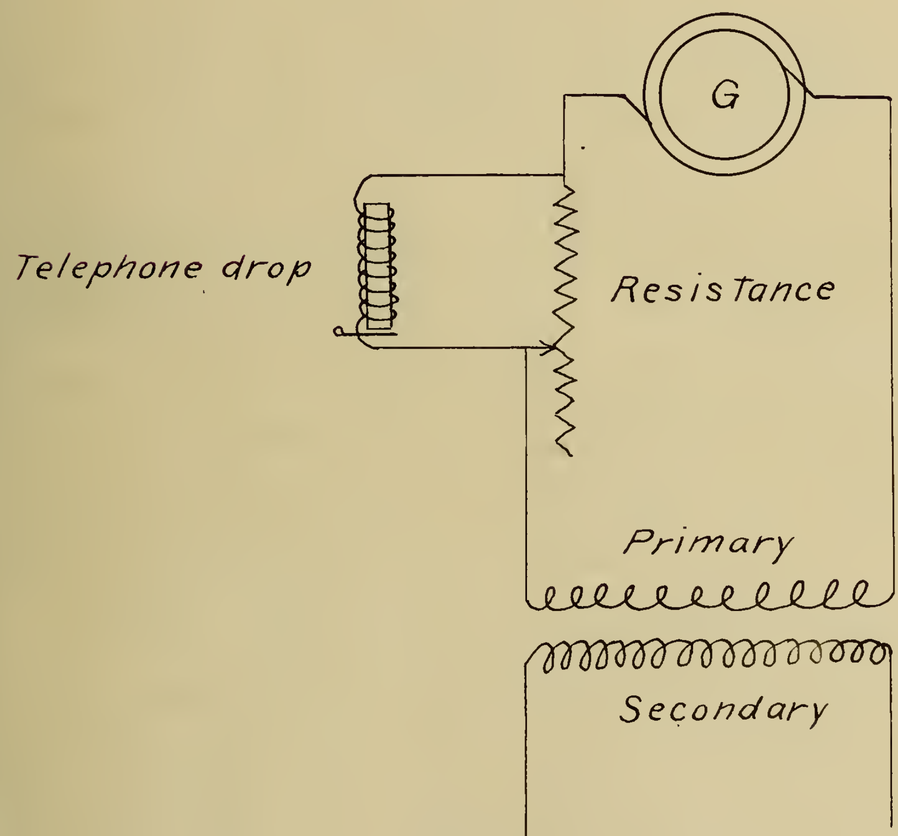


Fig. 12

is started suddenly or gradually. Since the impedance of the magnet coil u is constant for this actuating current, it will take a constant minimum E. M. F. to produce this constant current, i.e. to actuate the electromagnet necessitates a constant minimum potential difference across the non-inductive resistance, R. Calling this minimum potential difference E_{min}, the variable resistance R, and the primary current I

$$E_{min} = RI$$

$$\text{or} \quad I = \frac{E_{min}}{R.}$$

E_{min} is established once for all by means of a voltmeter. The variable resistance was in this case a 60 ohm rheostat, and this was calibrated for every contact point.

In performing the experiment the usual connections were made, (Fig. 4) with the arrangement mentioned above in the circuit. The primary was closed by means of the slip-ring attachment and the variable resistance, R, varied until, on closing the circuit, the electromagnet was barely actuated. Knowing E_{min} and R, the current was calculated. This operation was repeated for every 18 degrees along the E. M. F. wave.

RESULTS:- The result of this experiment is shown on plate 5 curves I, showing both the variation in secondary voltage, and primary current on closing the primary circuit. It is seen that, while the normal primary current, on open secondary, is 1.5 amperes, the current on closing the circuit rises as high as to 17 amperes, and never drops below 6 amperes, even at the best point of closing. It is also seen that the rush of current is the least when the secondary voltage is the highest and vice versa, i.e. if the primary is closed, when the E. M. F. is at the highest point on the wave, the current is small, while the time rate of change of current is large, as proved by excess secondary voltage test (see Art. IX.); and if closed on the zero point of the E. M. F. wave, the current rises to a much higher value, but the

rise is more gradual, producing less rate of change of flux and consequently lower secondary voltage. It must be borne in mind that these curves are not the actual waves, they show the variation of the first rush of primary current, and the variation of the initial secondary voltage on closing the primary circuit at different points of the E. M. F. wave.

XII. REMEDY FOR PREVENTING EXCESS VOLTAGES AND RUSH OF CURRENT ON CLOSING PRIMARY CIRCUIT:-

It has been stated previously in this report that the theory advanced to explain the rush of current, causing the excess voltage on closing the primary circuit, is that iron does not become magnetized at the instant of closing the circuit. This suggested a remedy, namely, to employ an inductance coil without iron core in series with the primary on closing the circuit. This was tried; the connections were similar to those shown in Fig. 4, with a core-less inductance of .01 henries in series with the primary. The method of conducting the test was like the one previously described in Art. IX., and values were obtained for the rush of current and secondary E. M. F. on closing the circuit every 18° along the E. M. F. curve.

RESULTS:- The results of these tests are shown by Table 4, plotted on Plate 5 curves II. It is seen that a marked reduction both in the primary rush of current, and secondary voltage is obtained by means of the coreless inductance, confirming the theory. The maximum secondary voltage has been reduced from 66000 volts to 62000 volts, or about 7%, while the primary maximum rush of current has been reduced from 17 amperes to 8 amperes, or about 50%.

With a larger inductance even more reduction may be possible, thus improving the conditions materially, reducing the liability of breakdown on closing the circuits.

The inductance, if employed to improve operating conditions, should, of course, be shortcircuited after the switches have been closed.

XIII. ACTUAL E. M. F. AND CURRENT WAVES ON CLOSING PRIMARY CIRCUIT AS OBTAINED BY OSCILLOGRAPH:-

To demonstrate further the rush of primary current on closing the circuit and its relation to the primary and secondary E. M. F.'s, it was decided to try to obtain the actual curves by means of the oscillograph. The connections for the current curve are shown in Fig. 13.

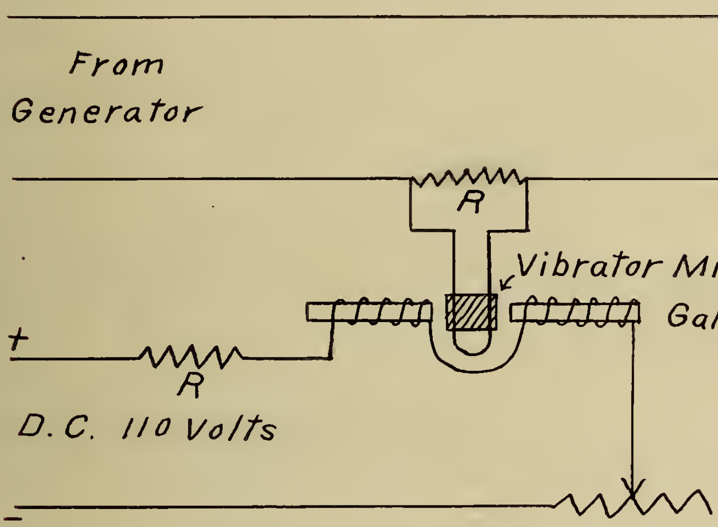


Fig. 13.

An iron wire R was placed in series with the primary circuit, and the vibrator of the oscillograph galvanometer was placed in shunt with this resistance.

The current curve was easily reproduced on the screen, and the rush on closing the circuit was beautifully shown. By closing and shortly afterwards opening the circuit continually at a definite point of the E. M. F. wave by means of our slip-ring attachment (see Art. VII.) without employing the cam, it was made possible to get an apparently permanent curve on the oscillograph screen, showing the actual current curve on closing the primary circuit. This curve was traced directly from the screen for every 18 degrees along the

E. M. F. wave, and the results are shown on Plates 6, 7, and 8. These curves show plainly that the current rush is largest on closing the circuit at the zero point of the E. M. F. wave, and least on closing it at the maximum points.

A similar set of curves were obtained with the .01 heury core-less inductance (see Art. XII.) in series with the primary circuit. These curves, shown on Plates 9, 10, and 11, show a material reduction of the rush of current on closing the primary with the core-less inductance in the circuit, verifying our previous experiment, described in Art. XI. As these curves do not prove entirely satisfactory, showing only one half of a cycle, and not showing the current in its relation to the primary and secondary E. M. F., it seemed desirable to have all three curves - primary and secondary voltage, and primary current - reproduced simultaneously on a photographic film on closing the primary circuit.

No difficulties were encountered in reproducing these curves on the screen, but owing to mechanical complications in connection with the oscillograph and lantern, relatively few of the total number of films exposed - amounting to about 50 films - are of any scientific value. The first set of photographs were taken on closing the circuit by means of the slip-ring attachment, in order to be sure to know on which point of the E. M. F. wave the circuit was closed. This operation was, however, found unnecessary, as the curves record the point of closing more definitely themselves. In taking the second set of curves an ordinary switch was, therefore, employed, closing the circuit at random. This made the operation of taking the pictures less complicated, and the results are more satisfactory.

Prints from the negatives thus obtained are shown on Plates 12, 13, and 14, these curves being the most representative curves obtained.

CAUSES OF EXCESS SECONDARY VOLTAGES ON CLOSING THE PRIMARY CIRCUIT:-

Very interesting deductions can be made from the curves obtained by means of the oscillograph.

1. They demonstrate in the first place that the theory described in Art. VI., namely, that the iron-core of an induction-coil does not become an magnetic at the instant of closing the circuit, does not hold true. It is seen from the oscillograph curves, that at the instant of closing the primary circuit the secondary E.M. F. immediately rises to its full value and even above. That this voltage is due to no other source than the magnetic inductance in the transformer iron-core is evident from the fact that the test coil employed was wound at right angle to the primary coils as shown in Fig. 14.

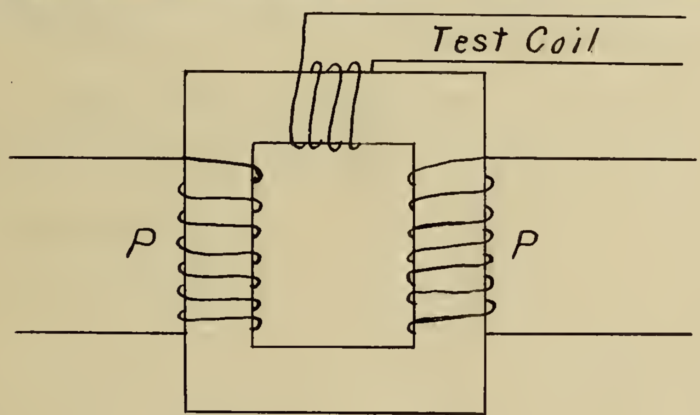


Fig. 14.

Although the theory referred to has thus proved to be wrong, it has been useful in suggesting ways and means of investigation, and of remedying the excess secondary voltages and the primary rush of current on closing the circuit. It was this theory that suggested a core-less inductance to be employed on closing the circuit, which proved to be a satisfactory remedy for the evils.

2. Secondly, the curves show that the excess secondary voltages are <u>not</u> due to the rush of current on closing the circuit, since this abnormal current occurs after the excess voltage has disappeared.

3. Thirdly, it is seen that on closing the circuit near the maximum point of the E. M. F. curve violent vibrations take place, both of E. M. F.'s and current. The primary E. M. F. rises in some instances 25% above normal, and this is only possible by a current passing in opposite direction to the E. M. F., causing a negative drop through the generator armature. The photographs verify this theory, showing the current in opposition to the E. M. F. when the latter rises above normal. The vibrations of the secondary E. M. F. correspond to those of the current. Hence the conclusion seems justified that the excess secondary voltages on closing the circuit are due to rapid vibrations of the current which in turn are due to the slots in the armature of the generator, and that the abnormal current occurring later has no effect as far as the initial excess voltages are concerned. We feel justified in saying that these rapid fluctuations of current are due to the slots in the armature, because they are of a frequency corresponding to the number of slots in the armature.

4. Although the rush of primary current due to closing the primary circuit on different points of the E. M. F. wave has no apparent effect upon the secondary voltage, it is interesting in this connection to note the peculiar shape of the current curve.

It is seen in the first place, that the rush of current is largest on closing the circuit near the zero point of the E. M. F. wave, and least on closing it near the maximum point of the same, verifying our previous experiments. It is further seen that the current rises to abnormal values only in one direction, then falls to normal in the opposite direction, and again rises abnormally - but not as high as before - in the same direction. This continues for several cycles, the peak becoming lower and lower for every succeeding cycle, and finally disappears.

An explanation of this phenomenon is here attempted:

Suppose the transformer iron is magnetized due to residual magnetism in the same direction in which the current will tend to flow on closing the circuit. This current will then have little effect upon the magnetic condition of the iron, and the rate of change of flux will be small, hence the counter E. M. F. or induced E. M. F. due to this flow of current will be less than normal, allowing an abnormal current to flow. As the current decreases to zero the residual magnetism remains in the iron, and any current tending to flow in the opposite direction will cause a large rate of change of flux, setting up a high induced E. M. F. which will immediately check the increasing current. This small current decreases - but does not remove - the original residual magnetism, and consequently a similar rush of current as took place on first closing the circuit will be produced at the beginning of the second cycle. As the residual magnetism gradually decreases, the rush of current will also decrease, and finally totally disappear, as the photographs show. This effect will be more pronounced on closing the circuit on the zero

point than on the maximum point of the E. M. F. curve, because on the zero point the E. M. F. is rising, while on the maximum point it is beginning to decrease. For the same reason the rush of current should be larger on closing the circuit on the rising part of the E. M. F. curve than on the decreasing part. If the iron is perfectly demagnetized the rush of current should be less than if it is magnetized in either direction. If magnetized in the opposite direction to that in which the current tends to flow, the current during the first half cycle will be normal. This normal current not being able to demagnetize the iron, will leave it magnetized in the opposite direction, and as the current starts in that direction, the current will cause a small rate of change of flux with the results stated above. The theory here advanced has not been verified by experiment otherwise than what the curves show; but it might easily be done by means of two similar transformers, connected as shown in Fig. 15.

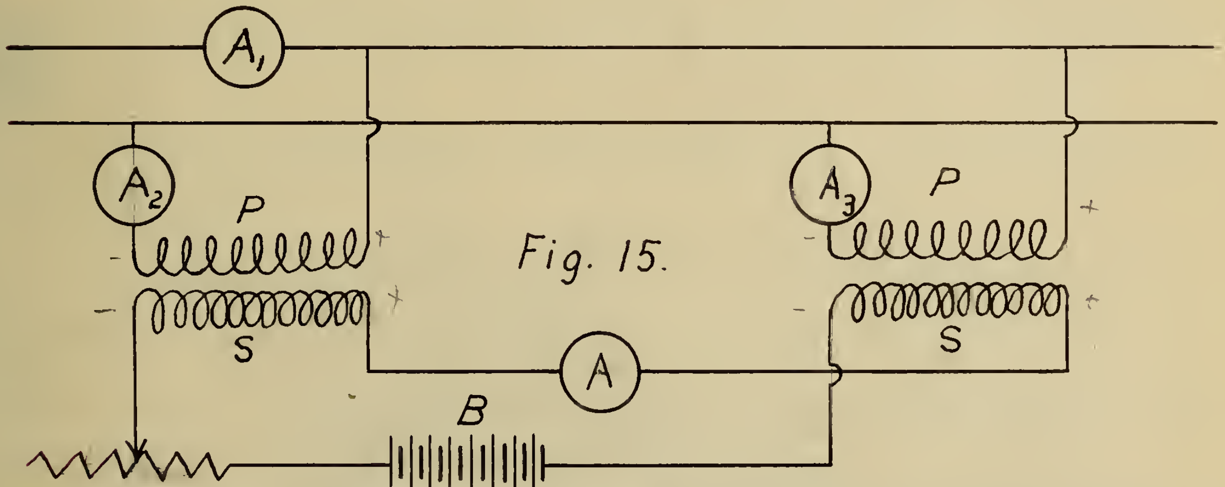


Fig. 15.

The primaries are connected in parallel, with an ammeter in circuit so as to register any circulating current. The secondaries are connected in opposition, with a battery and D. C. Ammeter in series, so as to magnetize the transformers in opposite direction. If the theory advanced holds true, Ammeter A_2 will register a circulating current, on closing the primary circuit, varying with the point of closing the circuit.

From what has been said it is evident that the rush of current will not be the same on closing the circuit on a given point of the E. M. F. wave unless the transformer iron is the same condition every time. The oscillograph curves give evidence for this; one photograph shows that on closing the circuit on the zero point there is practically no rush of current. The photographs show definitely on which point of the E. M. F. curve the circuit is closed, and no further explanation is needed.

SUMMARY:-

The following is a summary of the results of these investigations:

1. Excess secondary voltages occur on closing the primary circuit of a transformer at all points of the E. M. F. wave, the excess voltage being higher on closing the circuit on the maximum point of the wave than on the zero point. The variation of the excess voltage is from 10% to 40% above the normal secondary voltage of the transformer tested under the conditions at which it was tested.

2. These excess voltages are <u>not</u> dependent upon residual magnetism in the transformer iron.

3. These excess voltages are caused by a rapid variation of primary current on closing the circuit, appearing on the oscillograph photograph as three zig-zags. These variations of current are in turn due to the slots of the armature entering and leaving the magnetic field.

4. A rush of primary current follows the closing of the primary circuit. This current has no influence upon the secondary voltage, occurring after the excess secondary voltage has disappeared. It may, however, have damaging effects as it may rise as high as to 17 amperes, with a normal primary current of 1.5 amperes. The cause of this rush of current is the residual magnetism in the transformer iron, preventing an induced E. M. F. to

be set up in the primary winding. It takes considerable time for this residual magnetism to die down, and consequently the rush of current continues - gradually decreasing - for several cycles, but only during one half of each cycle.

5. To decrease the excess secondary voltages and rush of primary current on closing the circuit it is possible to employ a coreless inductance in the primary circuit on closing the switch. In the test where .01 henry was placed in series with the primary, a reduction of 7% of the normal secondary voltage, and of 50% of the primary rush of current, was obtained.

In the case where a generator is used independently on a line, the primary voltage may be brought up to normal while the transformer switch is closed; this will prevent both excess secondary voltage and rush of primary current.

A P P E N D I X.

RESIDUAL MAGNETISM THE CAUSE OF THE RUSH OF PRIMARY CURRENT ON CLOSING THE PRIMARY CIRCUIT.

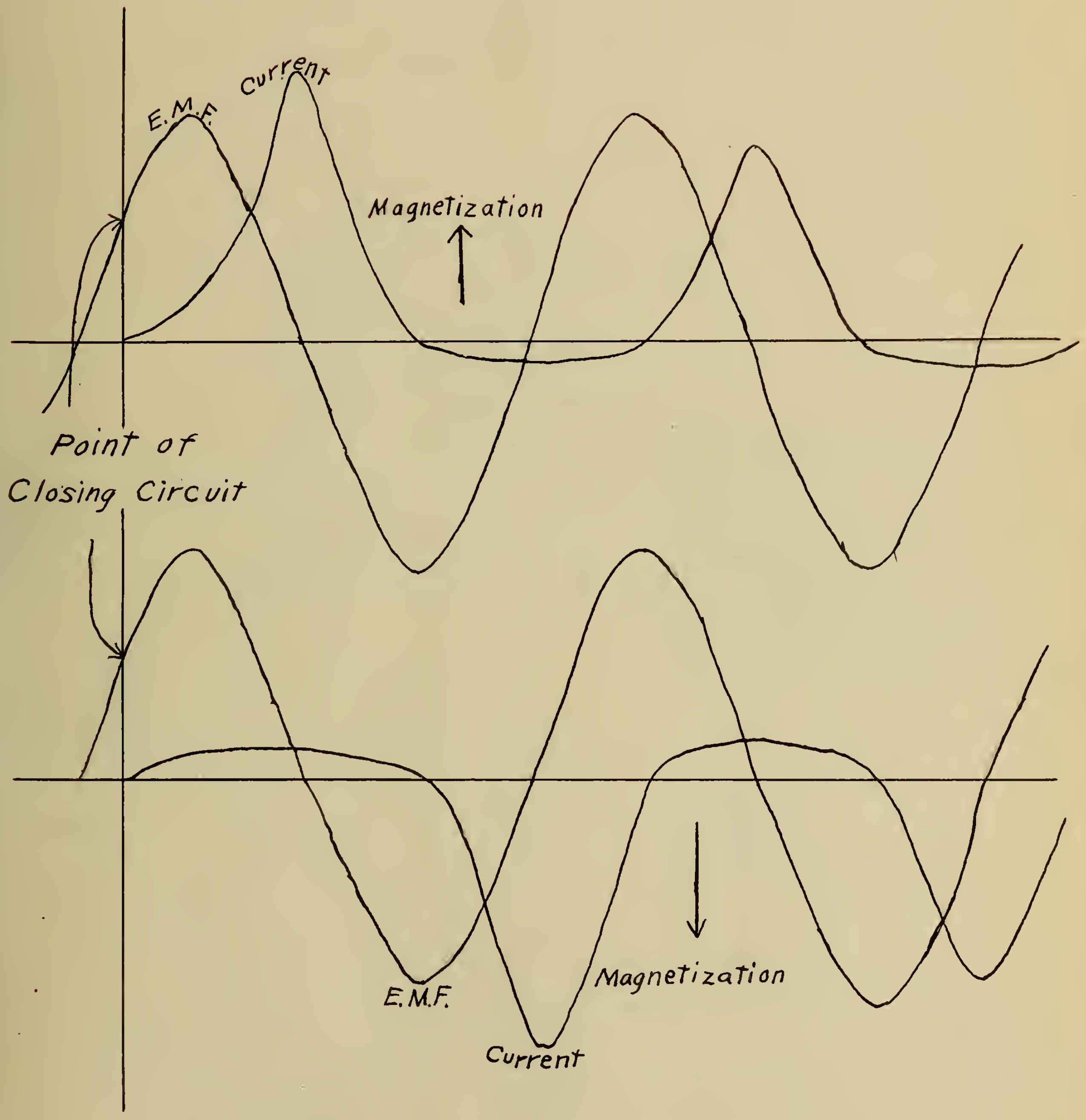
To verify the theory proposed in Art XIII p. 18 to explain the rush of current on closing the primary circuit, the test was performed, that was suggested in the same article. Connections were made as shown in Fig. 15. p. 19. The transformers employed were two 1 K. W. 10 to 1 transformers. 440 volts were impressed on the high voltage winding, and the low voltage winding was connected in series with a 110 volt storage battery and a lamp bank.

The theory is briefly as follows: If the two transformers be connected in opposition, no current will normally flow due to the primary winding; hence it should be possible to maintain a constant D. C. current in the secondary producing an effect equivalent to a constant residual magnetism in the transformer iron. The result will be a constant excess primary current on one side of the axis; and the peaks for one transformer will be in the opposite direction to those for the other, as illustrated in fig. 16. [1]

The first peak will vary in height, depending upon where, on the E.M.F. wave the circuit is closed. The magnetization is in the direction of the arrows.

If magnetized up to saturation, it is easily seen that the rush of the current must be very large in the primary in order to produce any rate of change of flux in the same direction as that of the magne-tism , hence the rush of current will depend upon the degree of magnetization, or upon the current in the secondary.

1. See next page



Current
E.M.F.
Magnetization
Point of
Closing Circuit
E.M.F.
Magnetization
Current

Fig. 16.

RESULTS:- With a current of 2 amperes in the secondary, there was practically no constant excess current in the primaries, while the rush on closing the circuit was quite material; and when there was a rush in *one* transformer, there was none in the other, confirming the theory. When the current in the secondaries was raised to 5 amperes, a constant excess current flowed in the primary. While the normal primary current on open secondary is .22 amperes, this excess current was 1.3 amperes. With increased secondary current this primary current increased to 5 amperes. The results are shown by the following table:

Table showing effects of Residual Magnetisms.

Secondary DC I_s	Constant Primary Excess AC. Current	Maximim Primary Rush of Current	Total Constant Primary Excess Current	
20	5	11.8	9.4	
17	4.3	10.8	7.7	
13	3.4	8.8	6.1	
9	2.4	7.5	4.3	
4	1.3	5.4	2.3	

This table shows besides the constant excess current also the rush of current on closing the circuit, and also the total current supplied to the transformers. It is seen that the total current in less than twice the current for one transformer, showing that part of the current is circulating between the transformers.

This test verifies the theory advanced and may be considered sufficient proof of the same.

Data for Determination of the E. M. F. Wave of the Generator							
Angle	Volts	Angle	Volts	Angle	Volts	Angle	Volts
0	0	95.0	115	189.5	23	284.5	118
9.5	17	104.5	125	199.0	43	294.0	122
19.0	42	114.0	113	208.5	67	303.5	110
28.5	61	123.5	104	218.0	82	313.0	106
38.0	82	133.0	95	227.5	98	322.5	87
47.5	93	142.5	68	237.0	110	332.0	73
57.0	102	152.0	58	246.5	113	341.5	52
66.5	112	161.5	45	256.0	120	351.0	27
76.0	110	171.0	19	265.5	119	360.5	4
85.5	113	180.0	0	275.0	120	363.0	0

Table No. 1.

Data for					
Voltages on Closing the Circuit at					
Different Points of the E.M.F. Wave					
Normal E.M.F. = 50000 Volts					
Transformer Demagnetized.					
Angle	Volts	Angle	Volts	Angle	Volts
0	56000	123.5	70000	256.0	68000
9.5	60000	142.5	59000	275.0	70000
28.5	64000	161.5	56000	294.0	71000
47.5	67000	180.0	54000	313.0	65000
66.5	71000	199.0	56000	332.0	60000
85.5	69000	218.0	58000	351.0	58000
104.5	71000	237.0	64000	370.0	57000

Table No. 2.

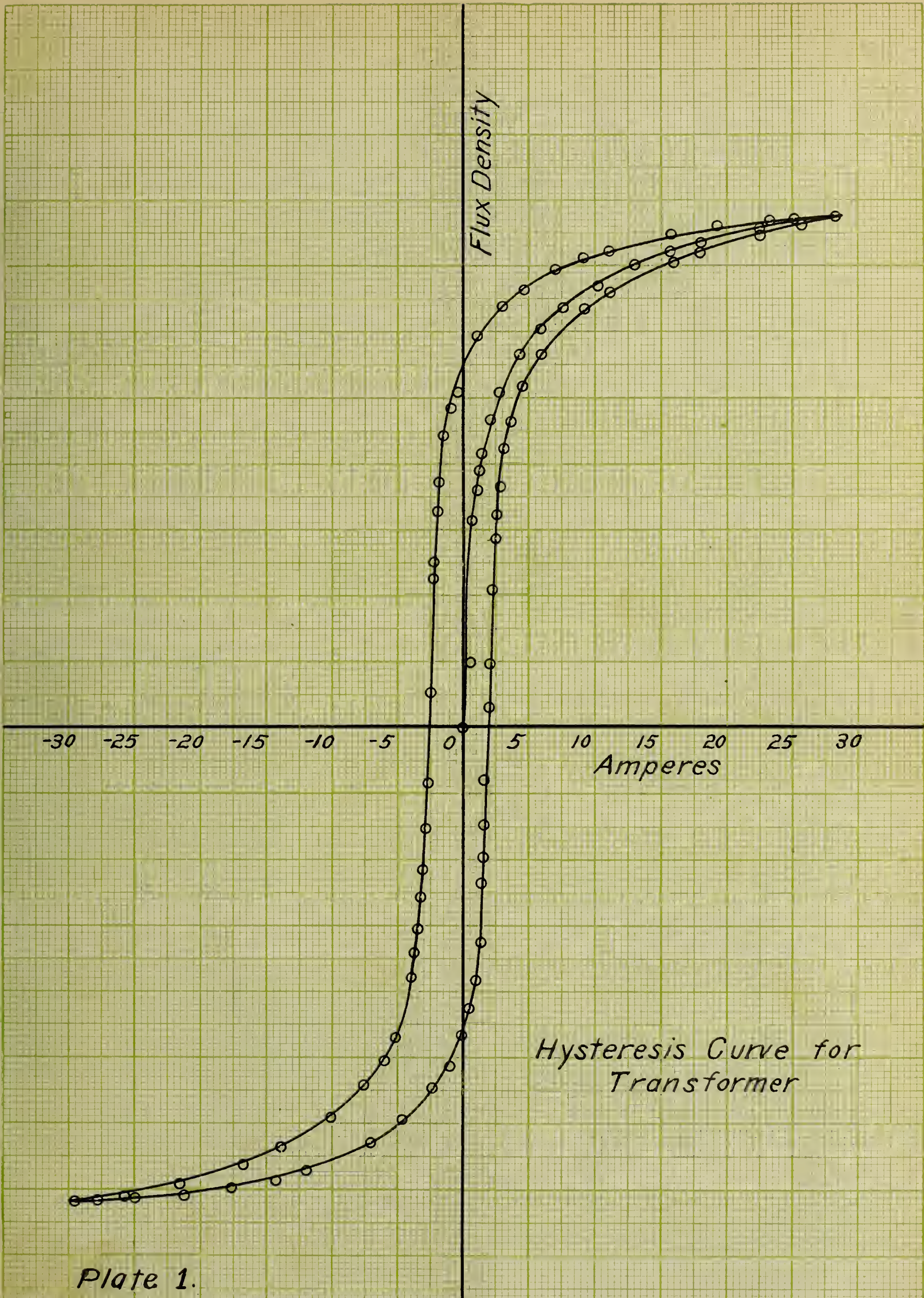
Data Showing that Residual Magnetism has no Effect on the Rise of Secondary Voltage on Closing the Primary Transformer Circuit. Normal E.M.F=50000 Volts.			
Angle	Transformer Magnetized		
	Positively	Negatively	Demagnetized
28.5	56000	56000	57000
47.5	65000	64000	64000
66.5	65000	67000	66000
85.5	64000	65000	67000
104.5	66000	67000	66000
123.5	63000	64000	64000
142.5	62000	62000	62000
161.5	58000	58000	58000
180.5	55000	54000	55000
199.5	58000	58000	59000
218.5	63000	62000	63000

Table No. 3.

Data Showing the Effect,
on the Primary Current and Secondary Voltage,
of Air Inductance in Series with Primary,
on Closing the Primary Circuit of the
Transformer. Normal E.M.F. = 50000 Volts

Angle	Without Inductance			With Inductance		
	Shunt Resistance	Primary Current	Secondary Volts	Shunt Resistance	Primary Current	Secondary Volts
28.5	2.7	15.2	56000	5.3	7.7	54000
47.5	2.7	15.2	64000	6.4	6.4	61000
66.5	4.1	10.0	66000	6.4	6.4	62000
85.5	5.3	7.7	65000	8.2	5.0	61000
104.5	6.4	6.4	66000	8.2	5.0	62000
123.5	8.2	5.0	64000	8.2	5.0	59000
142.5	5.3	7.7	62000	6.4	6.4	57000
161.5	4.1	10.0	58000	5.3	7.7	54000
180.5	2.7	15.2	55000	6.4	6.4	50000
199.5	2.3	17.8	58000	5.3	7.7	53000
218.5	2.3	17.8	62000	5.3	7.7	56000

Table No. 4.



EUGENE DIETZGEN CO., CHICAGO.

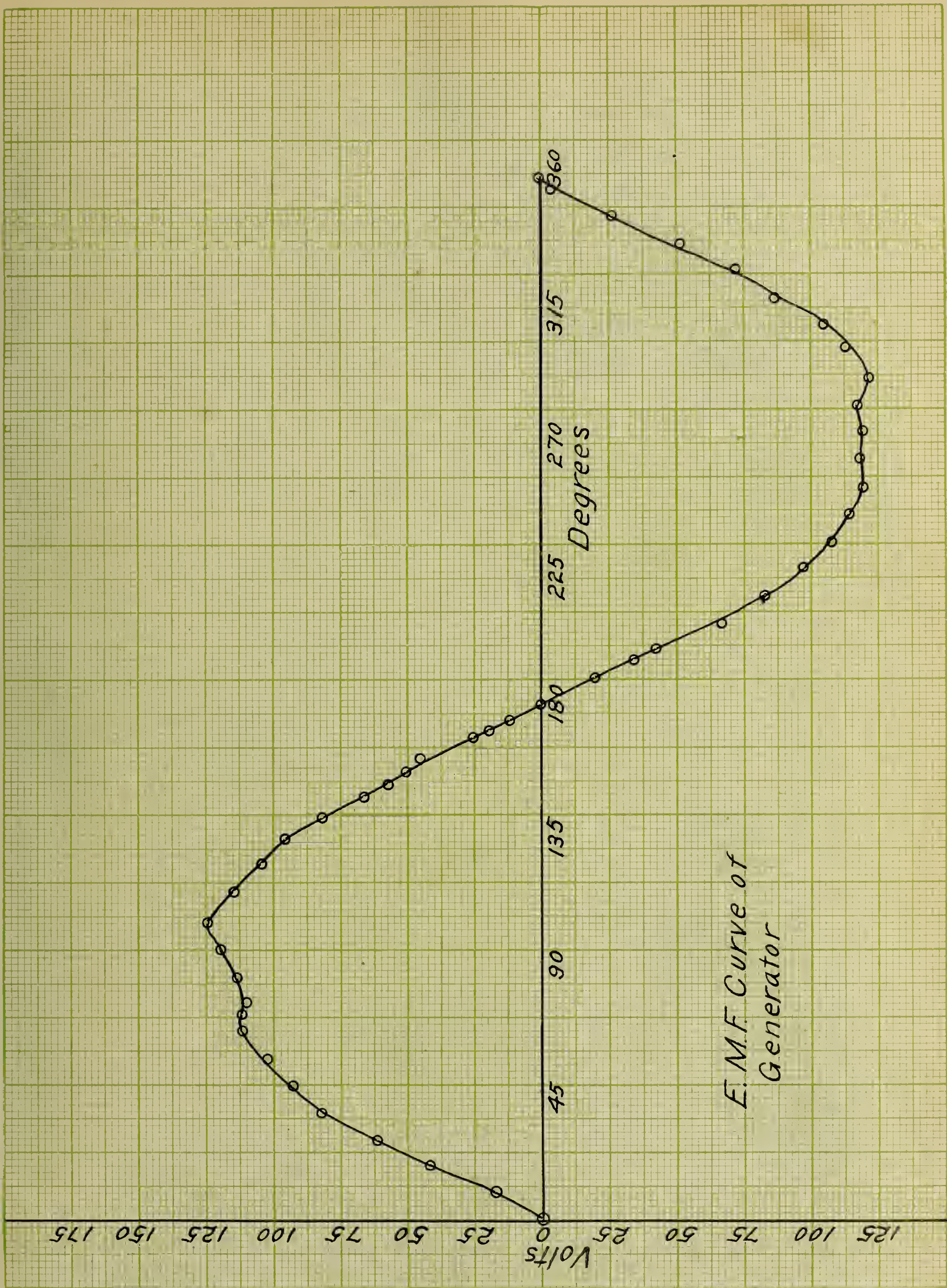
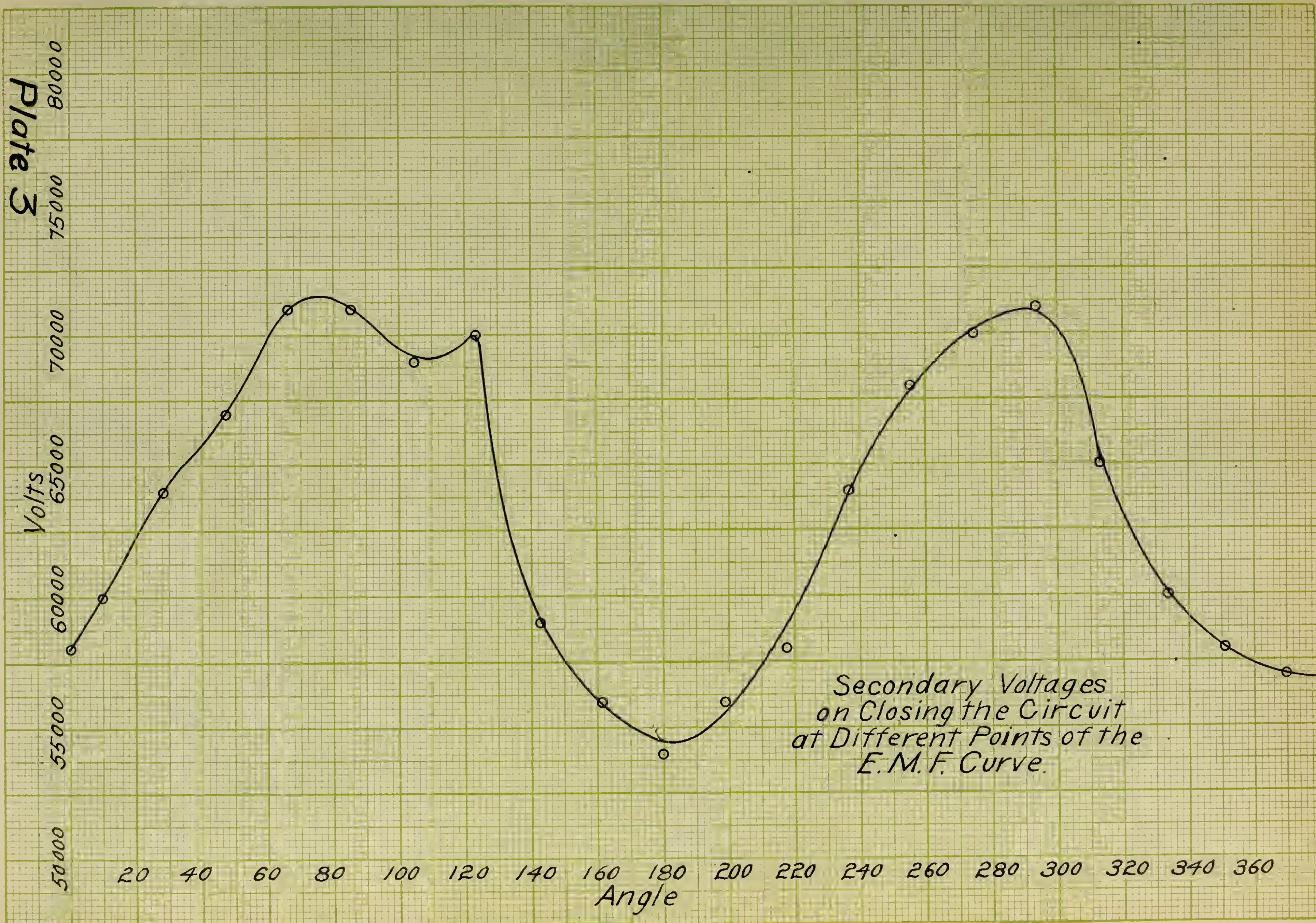
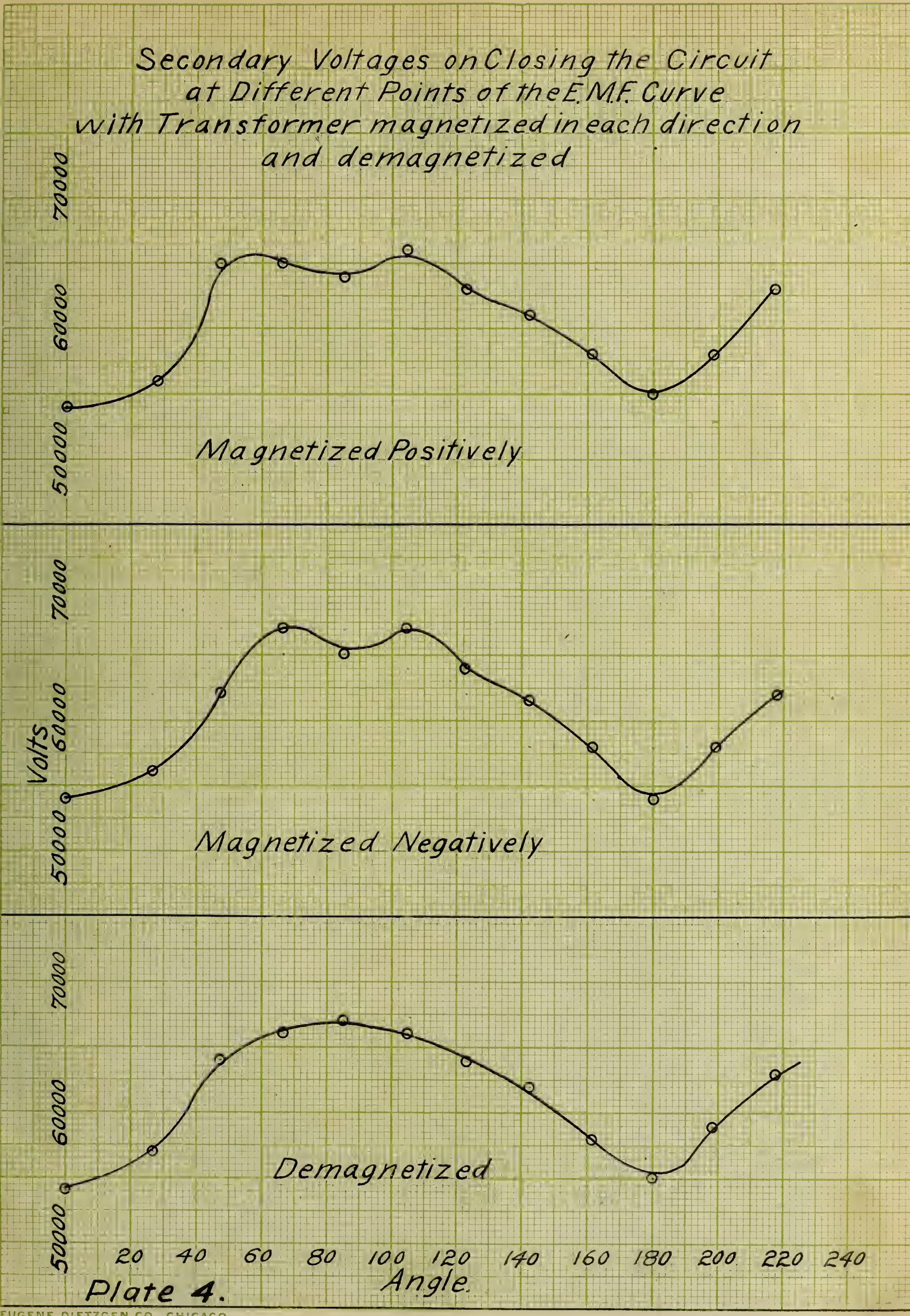

E.M.F. Curve of Generator
Degrees
0
45
90
135
180
225
270
315
360
Volts
175 150 125 100 75 50 25 0 25 50 75 100 125

Plate 2.

Plate 3


Secondary Voltages
on Closing the Circuit
at Different Points of the
E.M.F. Curve.
Volts
80000
75000
70000
65000
60000
55000
50000
Angle
20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360


Secondary Voltages on Closing the Circuit
at Different Points of the E.M.F. Curve
with Transformer magnetized in each direction
and demagnetized
Magnetized Positively
Magnetized Negatively
Demagnetized
Volts
50000
60000
70000
20
40
60
80
100
120
140
160
180
200
220
240
Angle
Plate 4.

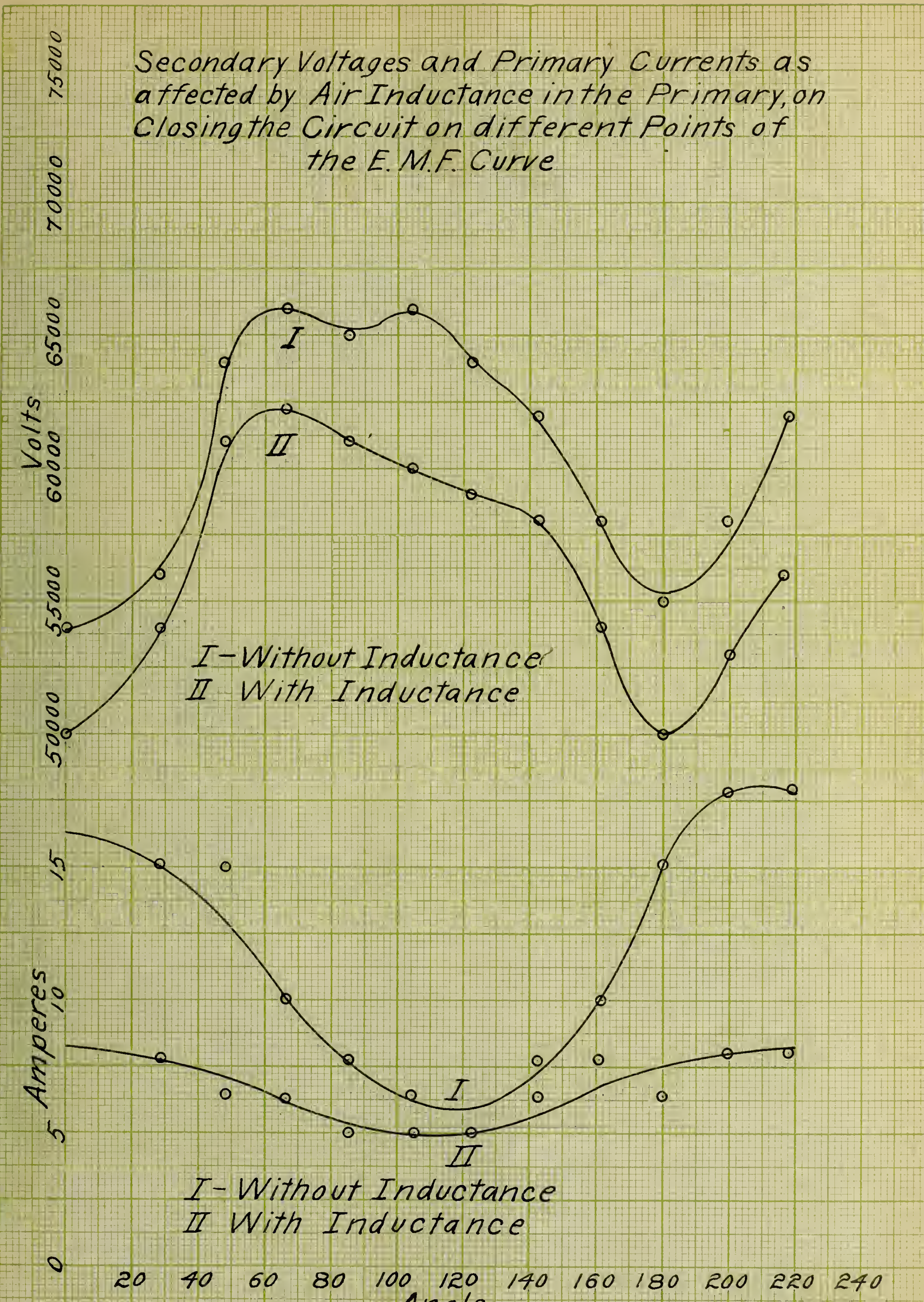

Secondary Voltages and Primary Currents as affected by Air Inductance in the Primary, on Closing the Circuit on different Points of the E.M.F. Curve
Volts
75000
70000
65000
60000
55000
50000
I
II
I–Without Inductance
II With Inductance
Amperes
15
10
5
0
I
II
I–Without Inductance
II With Inductance
20
40
60
80
100
120
140
160
180
200
220
240
Angle

Plate 5

Primary Rush of Current Curves
taken with the Oscillograph.

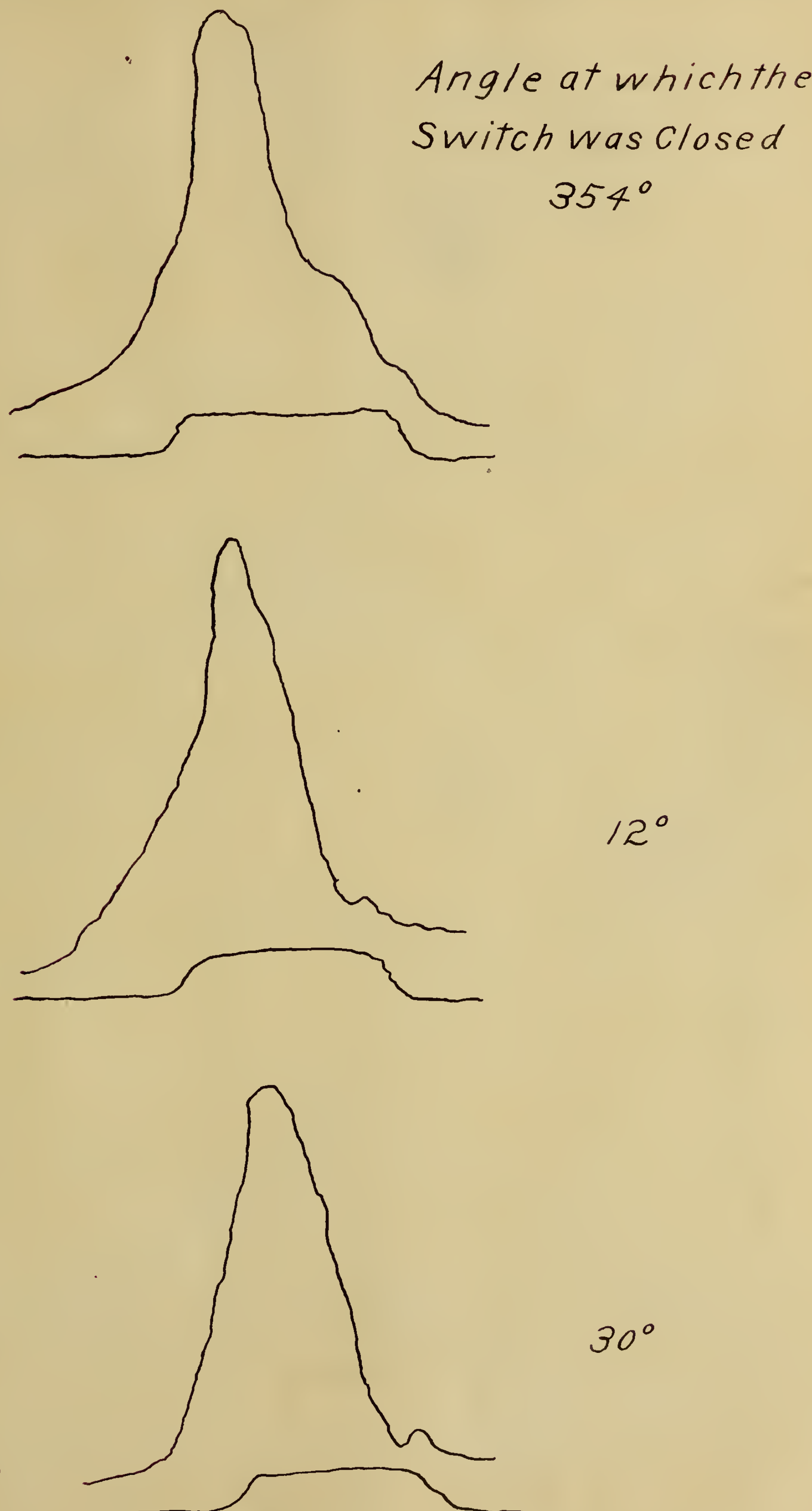


Plate 6.

48°

66°

84°

102°

Plate 7.

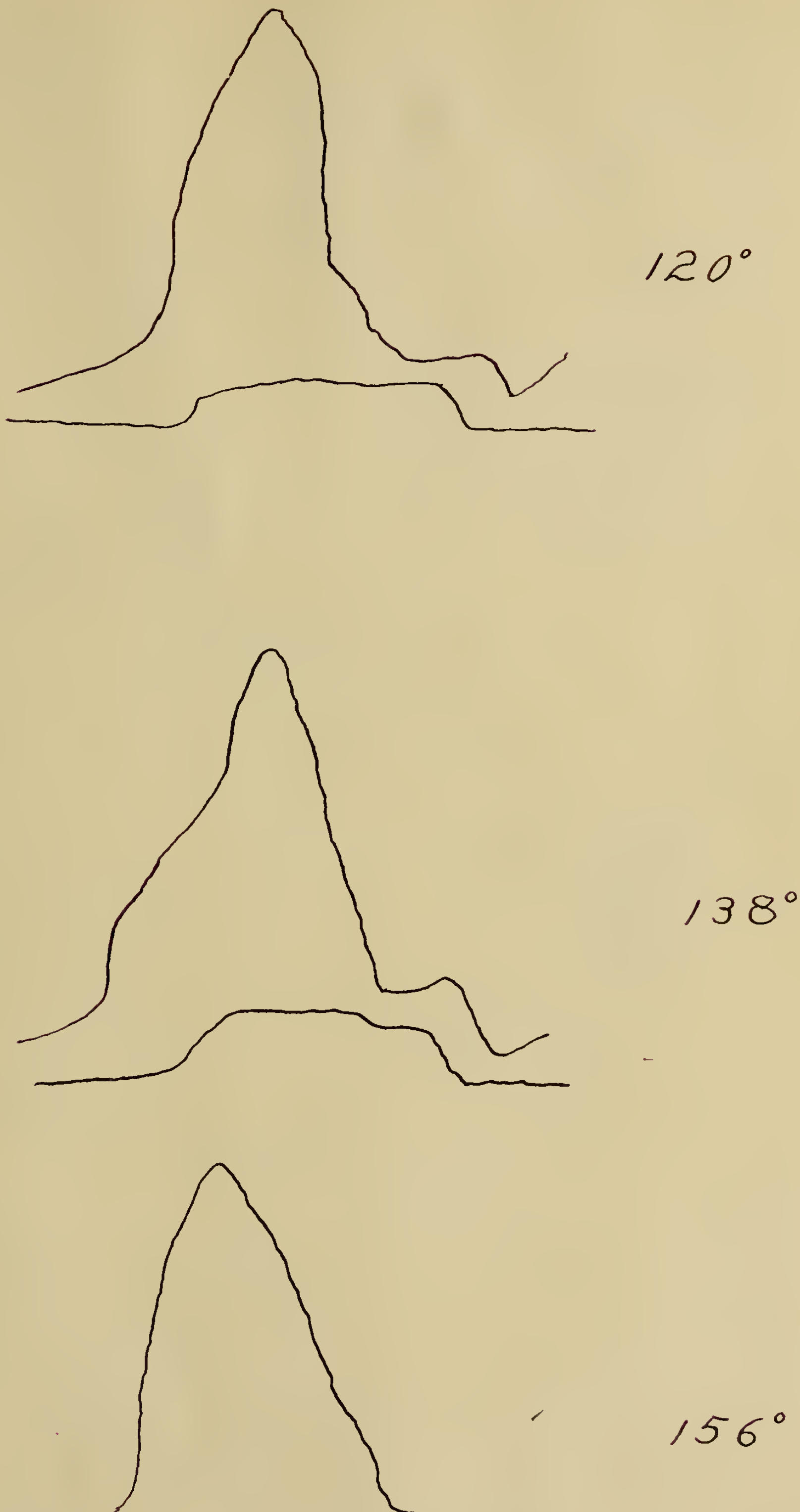


Plate 8

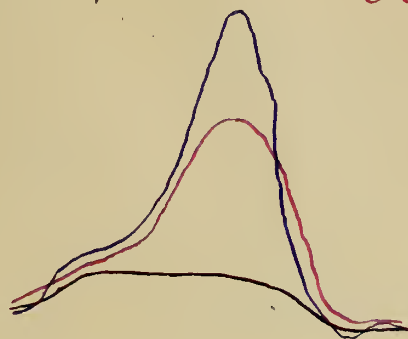
Oscillograph Current Curves showing the Effect of Air Inductance in the Primary Circuit on Closing and opening the Primary Circuit at Different Points of the E. M. F. Wave.

Normal Curve ——

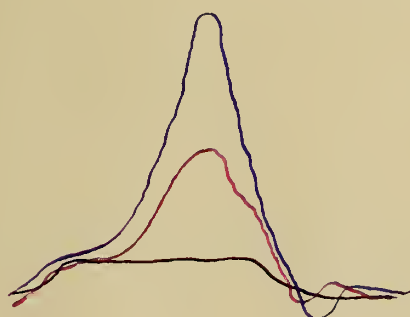
Curve Without Inductance ——

Curve Wilh Inductance ——

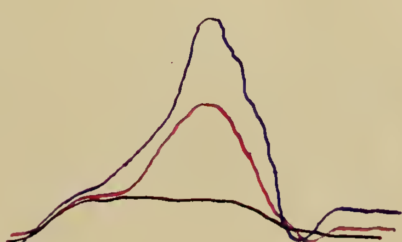
Angle at which Switch was closed



354°

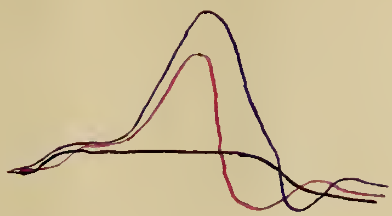


12°

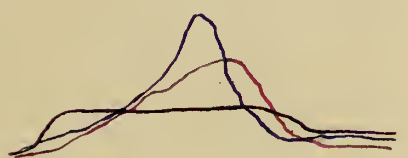


30°

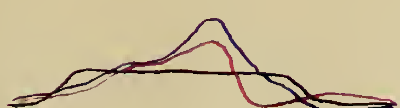
Plate 9.



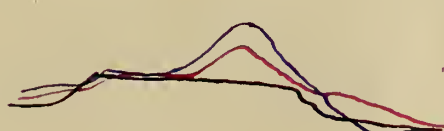
48°



66°

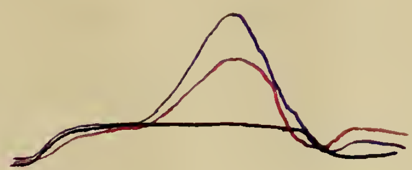


84°

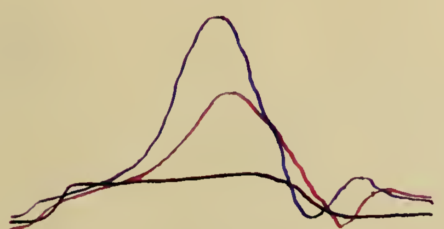


102°

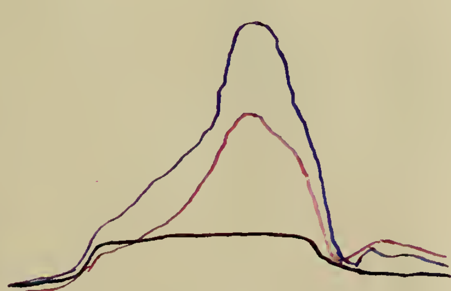
Plate 10.



120°



138°



156°

Plate 11

Plates 12. 13. 14, 15, 16, 17, + 18

Oscillograph Curves

of

Primary Voltage, Primary Current and

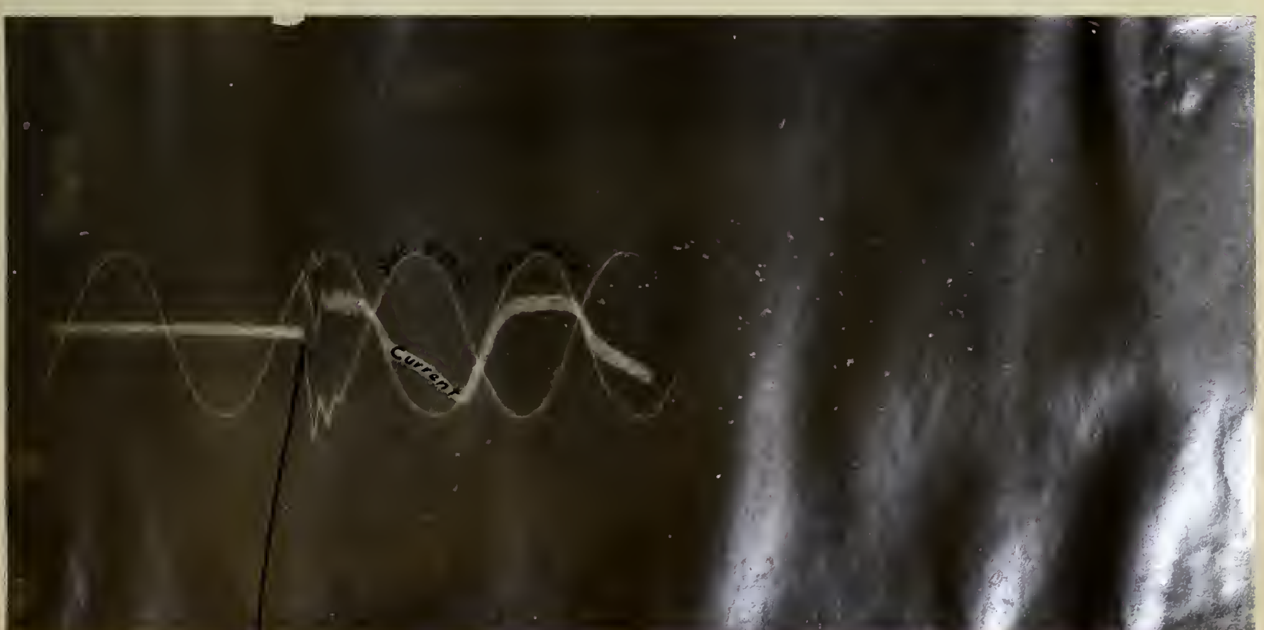
Secondary Voltage

Showing the variation of the same on closing the primary circuit at different points of the E.M.F. wave.

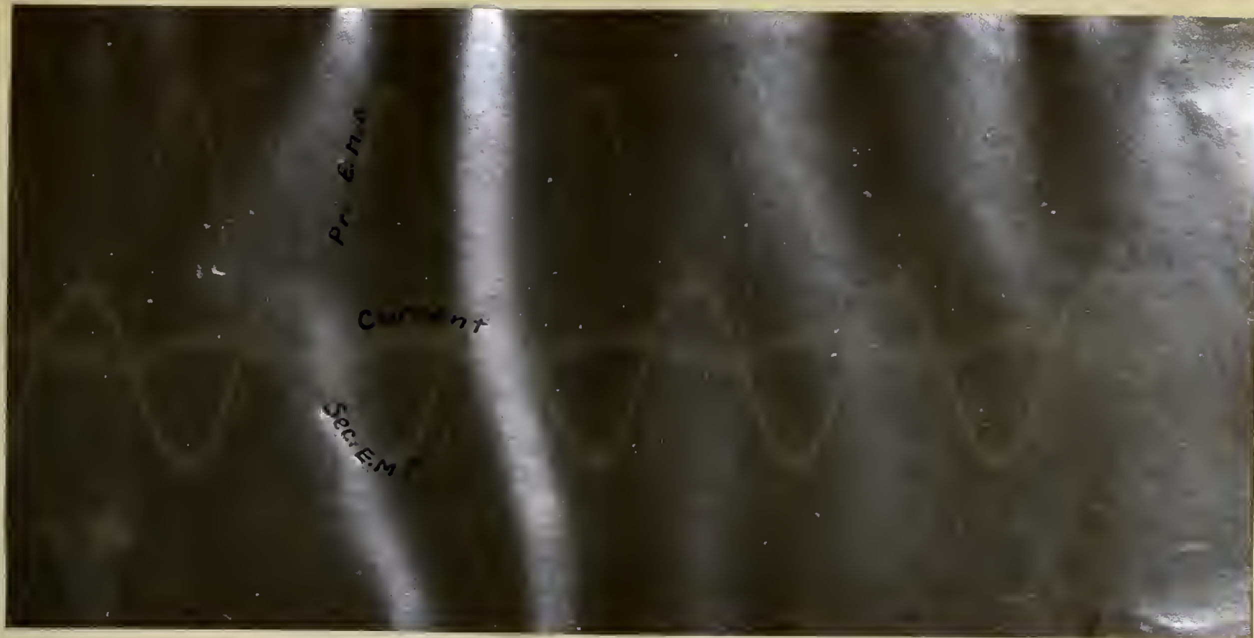
See Art. XIII page 14 + 15

These photographs are arranged so that those for closing on the zero point come first and those for closing on the maximim point last.

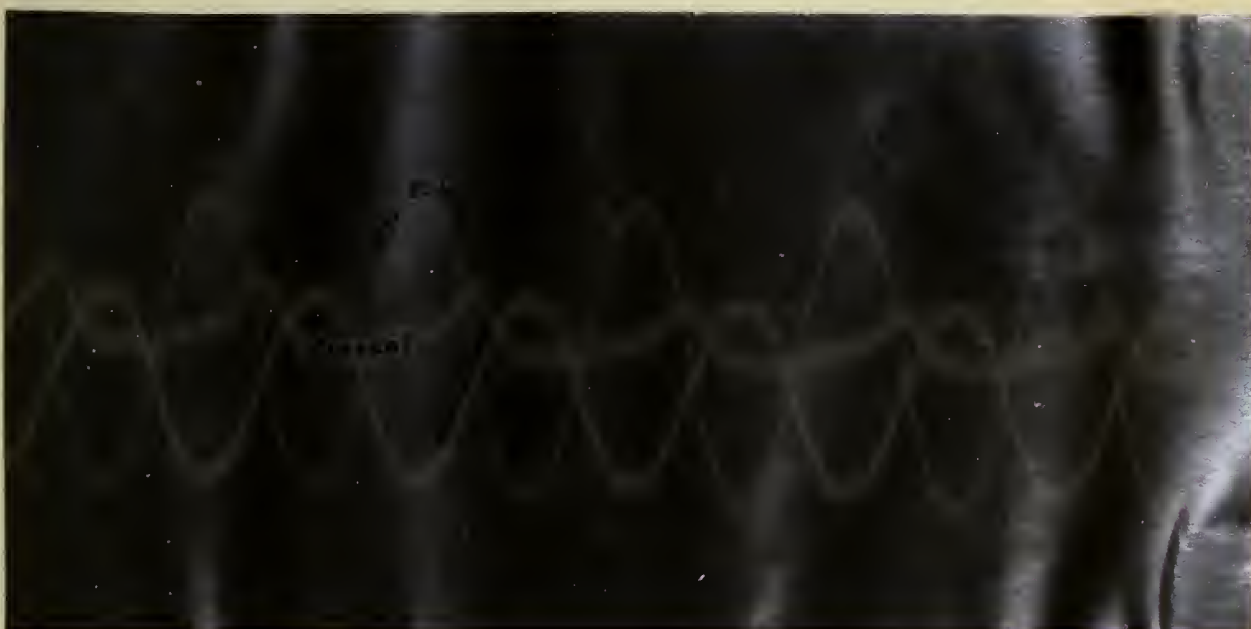
Sample



Point of Closing Circuit



Normal Operating Condition



Condition just after Closing Circuit

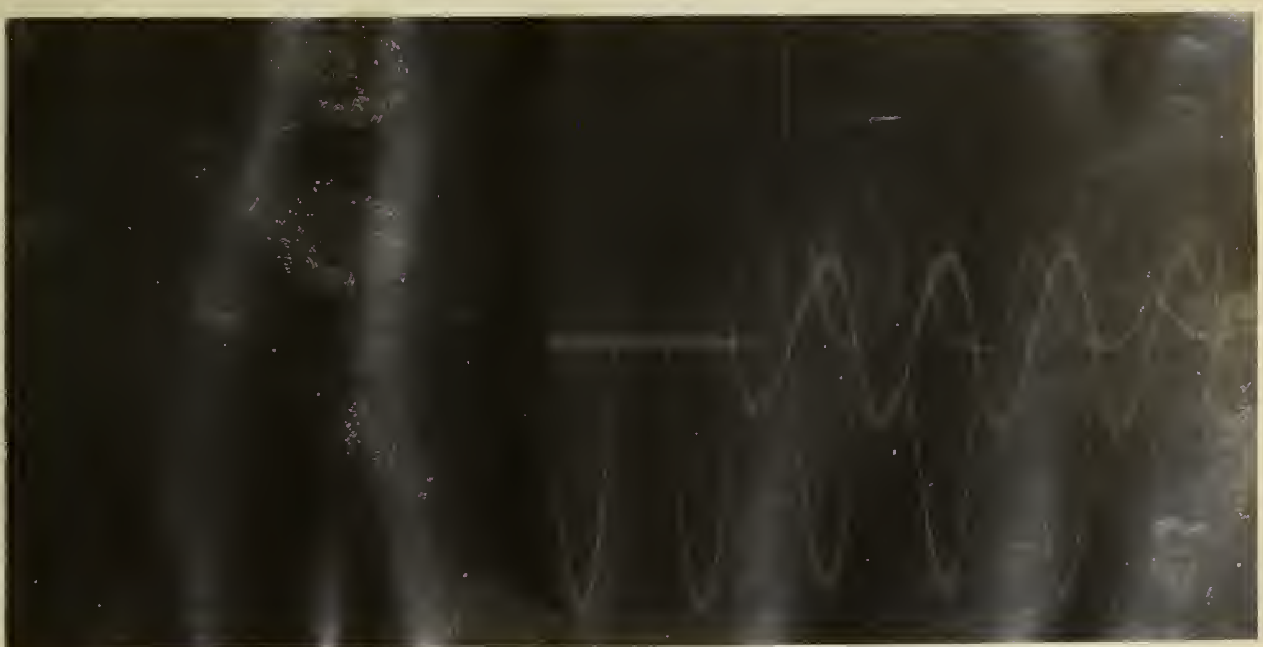


Plate 13.

Plate 14.

Circuit Closed near zero Pt. of E.M.F. wave, but in this Case there is no Rush of Current, as in previous Cases.

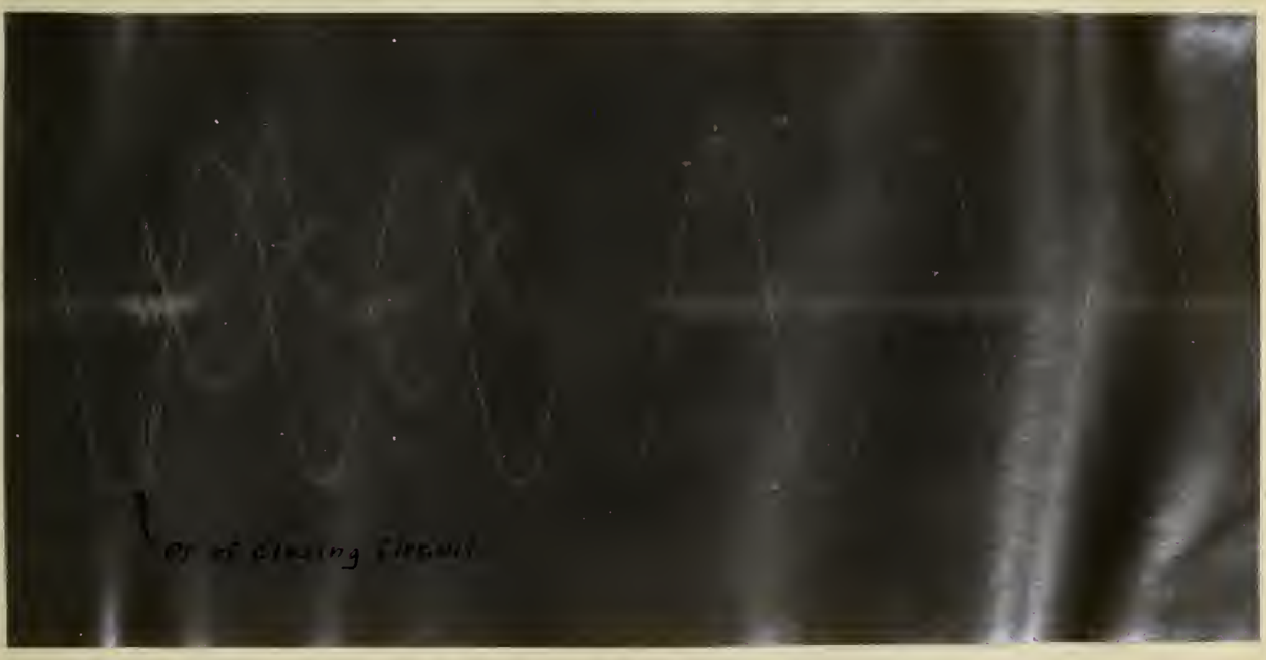
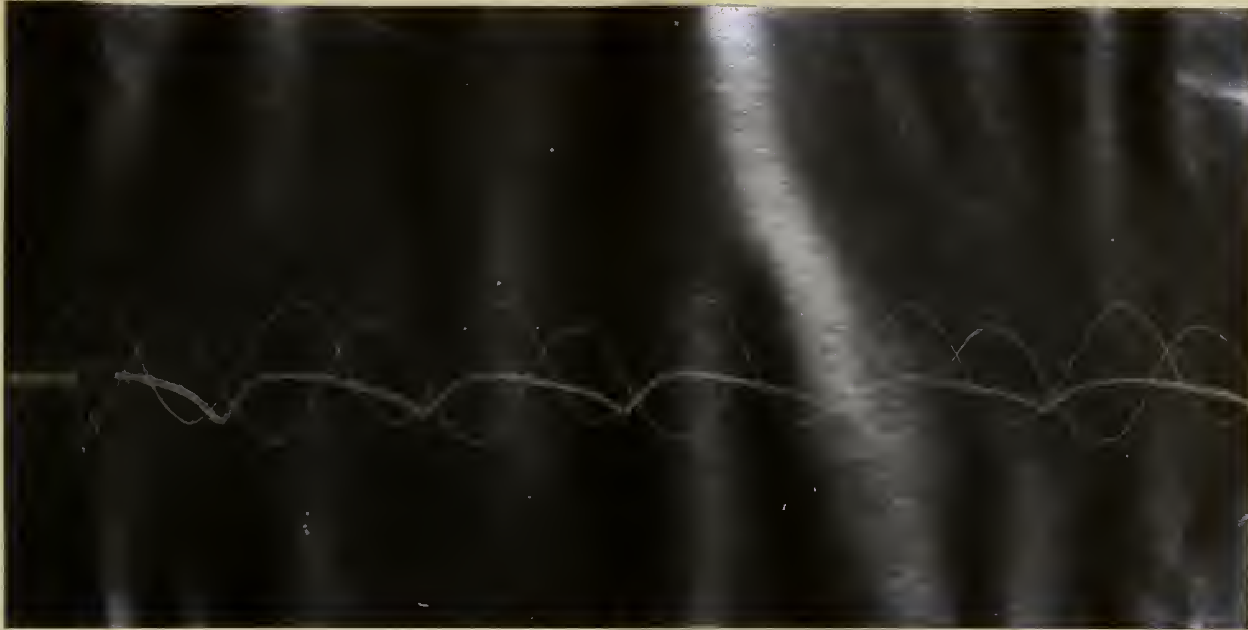


Plate 16.



Rush of Current in opposite Direction to prerious Cases, due to Resid. Magnetism.

Plate 17

Plate 18